Fermi National Accelerator Laboratory

FERMILAB-Conf-83/32-THY
April, 1983

Evolution of the Ultra High Energy Cosmic Ray Spectrum by Transport Equation*

Christopher T. Hill
Fermi National Accelerator Laboratory, P.O. Box 500
Batavia, Illinois, 60510

David N. Schramm
The University of Chicago, Chicago, Illinois 60637
and
Fermi National Accelerator Laboratory

Abstract

Ultra-high energy proton primaries interacting with the 3°K photon background are treated as a transport phenomenon. Baryon number is explicitly conserved and the evolved spectrum develops a bump at a scale of order 5×10^{19} eV, below the cutoff, due to the pile-up of energy degraded protons. This may correspond in part to the observed ankle structure in the CR spectrum.

---

*Contributed paper to the 18th International Cosmic Ray Conference, Bangalore, India, August 22, 1983.

I. Introduction

It is well known that at a scale of order 10^{20} eV the cosmic ray spectrum is expected to cut off due to the photoproduction of pions by collisions between the high energy cosmic rays (presumably protons) and the 3°K background photons (1). However, observations indicate that the spectrum is actually somewhat enhanced relative to an extrapolated lower energy spectrum, this enhancement onsetting at about 2×10^{19}eV (2).

Previous analyses of the cutoff(3), as well as models of the CR spectrum ankle(4), consider only mean attenuation lengths due to energy loss at energy E. While this is certainly valid at very high energies, $E>10^{20}$ eV, it breaks down when the energy loss factor varies rapidly with E, e.g. near threshold. Protons recoiling down from higher energies, $E'>E$ must be counted as additive contributions to the number at energy E, while the energy loss at E is purely subtractive. At energies of order 5×10^{19} eV this additive "pile-up" contribution dominates over attenuation by energy loss and the spectrum develops an enhancement. This effect is also anticipated by noting that baryon number must be conserved in photoproduction reactions, the minimum recoil energy is in practice always $> 10^{19}$eV, yet a differential spectrum attenuating everywhere like $\exp(-kx)$ has a decreasing baryon number with x.

We have constructed a spectrum evolution transport equation which correctly incorporates the dynamics of photoproduction physics in the cosmic ray frame and which yields exact numerical solutions for any x and input spectrum. It's solutions exhibit the proton pile-up phenomenon.

II. Spectrum Evolution Transport Equation

The evolution of the differential spectrum, $dN(E,x)/dE$ is given by the integro-differential equation:

$$\frac{\partial}{\partial x}\left(\frac{dN}{dE}\right) = -\int \sigma_t(E,\bar{E}_\gamma)\frac{dN}{dE}\ \rho(\bar{E}_\gamma)d\bar{E}_\gamma + \iint \frac{d\sigma}{dE}(E_0,E,\bar{E}_\gamma)\frac{dN}{dE_0}\ \rho(\bar{E}_\gamma)d\bar{E}_\gamma dE_0 \tag{1}$$

which formally resembles the Milne equation. What is new here is the inclusion of the second term on the rhs. which describes the downloading of the recoil protons to lower energies. $d\sigma(E,E')/dE'$ is the recoil proton differential cross-section which may be obtained above threshold from laboratory photoproduction angular distribution data at low energies, and from the single-particle inclusive proton distribution at high energies. These are boosted to the cosmic ray frame. We are primarily sensitive to the physics immediately above threshold in the resonance region for which extensive data exists(5). We use a typical leading particle distribution taken from pp scattering for the high energy behavior, to which we are less sensitive. We emphasize that equation (1) is exact; the problem is effectively one-dimensional in this frame.

We solve eq.(1) numerically. We include the appropriate 3°K longitudinal momentum distribution:

$$\bar{E}_\gamma = \frac{1}{2} E_\gamma(1+\cos\theta) \quad ; \quad \rho(\bar{E}_\gamma) \propto \bar{E}_\gamma^2 \int_1^\infty \frac{x dx}{\{\exp[(x\bar{E}_\gamma)/2T]-1\}} \tag{2}$$

It is readily verified that the total proton number is conserved (we neglect $p\bar{p}$ production, a negligible effect at these energies) while energy is lost to the pion production. This is used as a check on our numerical solutions.

In Figure 1, we plot the evolved $1/E^3$ differential spectrum through 3 to 50 interaction lengths corresponding to 100 microbarns, or ~8Mpc per interaction length. We clearly see the appearance of an enhancement due to the pile-up. It is not as large as the current data indicate.

Note that on the log-log plot increasing the photon temperature by a factor K shifts the curve left by log(K) units. Thus the absence of the bump below 10^{19}eV implies an upper limit on the photon temperature averaged over the source distance of roughly T<15°K.

If the present observations are corroborated by future higher statistics measurements, e.g. from the Fly's eye, etc. then an exotic mechanism may be required (e.g. "monopolonium" (6) or ref. (4)). Thus we also include in

Fig.1 an assumed real "ankle" in the primary spectrum. We assume $1/E^3$ up to $2x10^{19}$eV and $1/E^2$ above and the evolved spectrum is shown in the figure.

We emphasize that the proton pile-up should be observable and is conservatively expected at the level predicted by the evolved $1/E^3$ spectrum. We further emphasize that the shape in the 10^{19}eV to 10^{20}eV decade is determined primarily by the low energy lab photoproduction distributions and is fairly insensitive to the structure of the primary spectrum, except for overall normalization and source range. This is reminiscent of a "fixed point" behavior.

The resulting ν and γ spectra from pi decays should also reflect the pile-up and will differ, though perhaps not significantly, from earlier analysis results.

Further details will be discussed elsewhere. We thank Profs. Ed Berger, J.D. Bjorken and C. Quigg for illuminating discussions.

III. References

1. K. Greisen, Phys. Rev. Letters 16, 748 (1966); V. A. Kuzmin, G.T. Zatsepin, Zh. Eksp. Teor. Fiz. 4, 78 (1966).

2. G. Cunningham, et al., Astrophys. J. (letters) 236, 171 (1980); ibid., Proc. 15th Int. Conf. on CR's, Plodiv 2, 303 (1977); J. Linsley, in Origin of Cosmic

Rays, 53-68, ed. Setti, Spada, Wolfendale, (1981).

3. F. Stecker, Phys. Rev. 21, 1016 (1968); A.W. Strong, J. Wdowczyk, A.W. Wolfendale, J. Phys. A, Math, Nucl. & General 7, 120 (1974); ibid., J. Phys. A., Math, Nucl. & Gen. 7, 1767 (1974); A.M. Hillas, Canadian Journal of Physics 46, 8623 (1968).

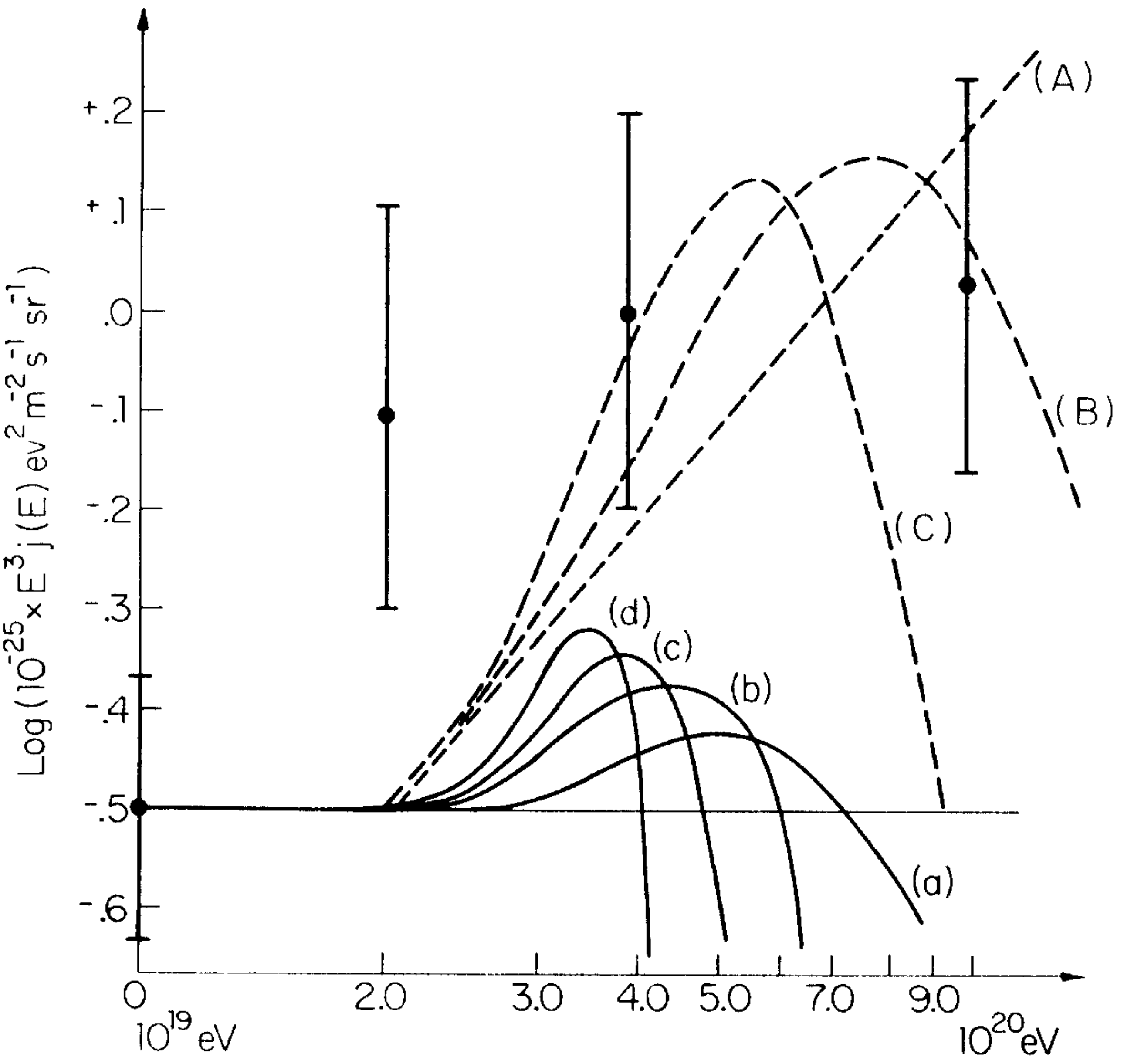
4. M. Giler, J. Wdowczyk and A.W. Wolfendale, J. Phys. G.; Nucl. Phys. 6, 1561 (1980).

5. A. Donnachie, Proceedings, 1971 Int'l Symposium on Electron & Photon Interactions at High Energies, Cornell University; B. Wiik (Same Conference Proceedings); H. Genzel and W. Pfeil, Photoproduction Data below 1.5 GeV, Bonn Univ. PI BI-168, 1972.

6. C.T. Hill and D.N. Schramm, this conference, and in preparation.

Figure Caption

Solid lines denote evolved $1/E^3$ spectrum through (a) 3 interaction lengths (il.); (b) 10 il.; (c) 20 il.; (d) 50 il. Dashed lines denote $1/E^3 \rightarrow 1/E^2$ for $E > 2\times10^{19}$eV: (A) primary spectrum; (B) 3 il.; (C) 8 il. Data points are indicated from ref. (4) for comparison.



(A)
(B)
(C)
(a)
(b)
(c)
(d)
+.2
+.1
.0
-.1
-.2
-.3
-.4
-.5
-.6
Log$(10^{-25} \times E^3 j(E)\ ev^2 m^{-2} s^{-1} sr^{-1})$
0
2.0
3.0
4.0
5.0
7.0
9.0
10^{19} eV
10^{20} eV

Figure 1